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TRANSPORTATION TO EARTH ORBIT: 1975-1985

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by

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INTRODUCTION

It is now generally recognized that the major cost of operating a space station will result from the transportation of crew and passengers to and from orbit. It is also clear that the Saturn/Apollo systems that we will inherit from the lunar program are not well suited to this job of transportation; the launch vehicle is too big and the spacecraft too small, and both have been designed to use once and throw away. If we attempted to use the Saturn/Apollo System at current costs, for logistic support of a 12-man station, for example, assuming 3-monthly resupply, the transportation cost would exceed $1 Billion/yr.

When we consider the alternatives for a successor to the Saturn/ Apollo system, a number of questions arise: What are the prospects for reducing transportation costs to levels substantially below those of current hardware? What changes in development and operating philosophy must we adopt in order to realize such reduced costs? What investment is required to develop this more effective system? And finally, what technology should we pursue now in order to best prepare for its development?

This paper reviews some of the general concepts that have been proposed in the past; discusses the preformance and cost characteristics of these concepts, and takes a more detailed look at the more promising configurations. Finally, some remarks are made regarding technology items that should be given emphasis in the future.

COST/PERFORMANCE CONSIDERATIONS

In Figure 1, several representative configurations have been arranged in a matrix according to the number of propulsive stages they employ and according to the degree of reusability of the system--from expendable, through partly reusable, to completely reusable. Many of these configurations have seen a great deal of study by NASA and by the industry in the past.

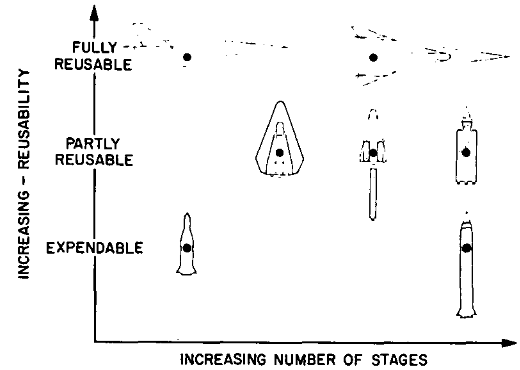


FIGURE 1 - General Concepts

The configuration at the lower right represents the kind of system operating today: completely expendable with several stages of propulsion. At the lower left is a single stage to orbit expendable system. In the center row are shown partly reusable systems, in which the spacecraft is reused and at least part of the launch vehicle is expended (the open part of each configuration indicates the reusable portion): on the right a 3-stage system; in the center, a 2-stage system in which the upper stage propulsion is incorporated into the spacecraft; and on the left the so-called 1-1/2 stage system in which only the tanks are expended.

In the top row, in the center, is shown a 2-stage completely reusable system in which the 1st stage, either a rocket or airbreathing system, flies home suborbitally. On the left, a single-stage-to-orbit reusable system--the old aerospace place concept of several years ago.

Some of these configurations, the single-stage reusable aerospaceplane for example, are not feasible by any reasonable extension of present day technology. Others, although technically feasible, offer little hope of low cost operation; the all-expendable systems, in particular, fall into this category.

If we apply the criteria of adequate performance and of potential for low cost to these various concepts, we can superimpose some rough boundaries on the matrix and define a region that contains the kinds of systems that appear both technically feasible and economical. This region of interest is identified in Figure 2.

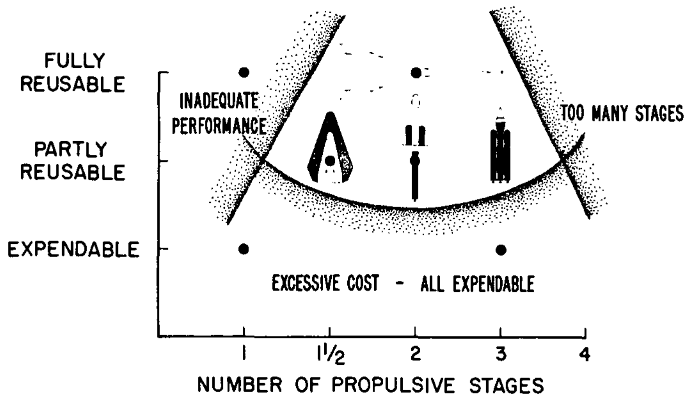


FIGURE 2 - Performance/Cost Boundaries

The diagonal line on the left is a marginal performance boundary. Configurations near this line have marginal performances in the sense that the useful payload delivered to orbit may be small compared with the inert weight of the system. Configurations to the left of this line have inadequate performance, and configurations to the far right have substantial performance margins--in particular, the multiple stage partially reusable and expendable systems.

The right hand diagonal forms a boundary beyond which there are too many stages for the purpose of delivering payload to Earth Orbit and these result only in unnecessary cost. It is not necessary to have four stages to attain orbital speed; moreover, even a 3-stage reusable system becomes costly because of the difficulty of recovering the middle stage (the first and third stages are much more easily recovered).

The horizontal boundary at the bottom recognizes that the all-expendable systems, including launch vehicle and spacecraft, are just too costly to throw away. Having focused our attention on this region, we can take a closer look at some of the concepts. On the right is depicted a semi-ballistic spacecraft, comprising a crew module and a cargo/propulsion module, both reusable; and boosted by a low cost launch vehicle. The launch vehicle shown consists of three solid rocket motors.

Moving to the left, the configuration becomes a two-stage system in which the second stage is incorporated into a reusable core spacecraft; because of the greater amount of propulsion and fuel in the spacecraft, it tends to become larger and longer than the ballistic system, and would land horizontally; expendable tip-tanks may be required in order to accommodate the necessary fuel.

Moving to the extreme left, now, and dispensing with the first stage altogether, the tip-tanks are further enlarged to accommodate the large increase in fuel, and the configuration evolves into the so-called stage and a half. The core, now with additional engines, is reusable. The alternative to this stage and a half is to place the upper stage core spacecraft on a reusable lower stage, which then gives us the two-stage reusable system depicted at the top of Figure 2. This first stage can be either a Vertical Takeoff Rocket or a Horizontal Takeoff Airbreathing System; in either case, it returns to Earth and lands horizontally, after releasing the second stage.

LOW COST LAUNCH VEHICLE CHARACTERISTICS

Let me draw some further distinctions among the concepts that have survived this first sorting-out process. In Figure 3 are listed three important characteristics which bear on the extent to which these concepts depart from our past systems experience. In terms of these characteristics, three configuration classes are defined:

> *Class I* systems have evolved from our past systems, have adequate performance margins and are partly reusable.
>
> *Class II* have not evolved from past systems, have adequate performance margins and are partly reusable.
>
> *Class III* have not evolved from past systems, may not have adequate performance margins and are fully reusable.

We probably have greatest confidence in being able to develop Class I systems and least confidence in being able to develop Class III systems.

CHARACTERISTICS

	EVOLVED FROM PAST SYSTEMS	ADEQUATE PERFORMANCE MARGIN	REUSABLE
CLASS I	YES	YES	PARTLY
CLASS II	NO	YES	PARTLY
CLASS III	NO	NO	FULLY

FIGURE 3 - Classification of Concepts

The reusable semi-ballistic spacecraft with the low cost launch vehicle falls in Class I; when the spacecraft is replaced by a lifting configuration which incorporates a major part of the propulsion, retaining a low-cost first stage, it falls into Class II and when that spacecraft is placed on a reusable first stage, it becomes a Class III system.

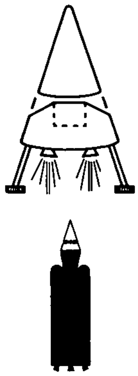
The logistics systems are considered to be capable of carrying nine men and a cargo of 15,000 pounds; however, if this is changed to six or twelve men and up to 20,000 pounds of cargo, the general conclusions would not be changed.

Costs are considered somewhat more parametrically, and a distinction is made between cost estimates that are based on past NASA experience, and cost estimates that assume very different test and operations philosophy, and generally lead to much lower costs. When the latter assumptions are made, the results are frequently very optimistic with respect to costs per flight.

In the years immediately ahead, it seems unlikely that we will make discontinuous changes in our test and operations philosophy and I believe that cost estimates based on past experience will be more valid. More generally, for the future, we must reexamine past philosophy and make major departures from past practice if we are to realize the low cost system that permits routine transportation to and from orbit.

CLASS I SYSTEMS

Looking at the Class I systems now, which have been defined as evolving from past systems and having adequate performance, we should be concerned primarily with their costs. Figure 4 depicts what a typical low cost Class I system would comprise. The crew module is similar in principle to the previous Gemini and Apollo Command Module except that it is reusable. It also permits on-board checkout of the whole system and in this sense has some of the features of the Apollo Lunar Module. Its weight is of the order of 12,000 pounds, is 150 to 180" in diameter and is capable of land landing.



SYSTEM	PREVIOUS RELATED DEVELOPMENTS
CREW MODULE	GEMINI, APOLLO CM, LM
PROPULSION MODULE	APOLLO CM
PROPULSIVE LANDING	APOLLO LM
156 SRM	TITAN III M (120 SRM)

FIGURE 4 - Class I — Low Cost Configuration

The propulsion module, which may also contain cargo, is also reusable, 220 to 260" in diameter, has a dry weight of the order of 15,000 pounds and contains 40,000 to 50,000 pounds of storable propellant--N_2O_4-A50 was assumed here--and is similar in general performance to the Apollo Service Module. It serves as the orbital injection stage, provides maneuvering and deboost ΔV for the crew module. It enters the atmosphere separately from the crew module and uses propulsive touchdown, after parachute descent.

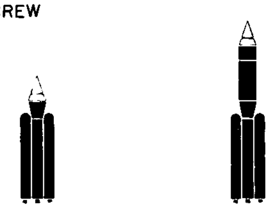
As experience is gained with this landing mode, it may be possible to enter the crew and propulsion modules as an integrated unit with the crew in control of the propulsive landing, in direct analogy with the lunar landing.

The launch vehicle considered here is a two-stage vehicle, the outer solid rockets forming the first stage and providing about 8,000 ft/sec, the center solid rocket being the second stage and providing about 12,000 ft/sec. The 156" rockets are segmented and similar in principle to the 120" motors of the Titan IIIM, although they require further development. An alternative launch vehicle might consist of a 2-stage monolithic solid rocket of 260" diameter.

Elaborating a little further in the flexibility that this approach provides, the basic configuration shown in Figure 5 can carry

15,000 pounds of cargo with a nine-man crew, or 25,000 pounds cargo as an unmanned logistics vehicle. In this latter mode, the propulsion module is controlled initially from the ground and subsequently from the space station. For larger payloads, up to 80,000 pounds cargo, the same configuration with an improved S-IVB (using J2S engines) having lower costs than the current system, is used as an upper stage.

9 MAN CREW



CARGO, lb	15,000	25,000 (NO CREW)	80,000
156 SRM	•	•	•
IMPROVED SIVB	–	–	•
EXP CARGO MOD	•	•	•
REUSE CREW MOD	•	–	•
REUSE PROP MOD	•	•	•
RECURRING COST, $M	20	15	35

FIGURE 5 - Class I — Low Cost Family

The potential recurring costs for this family of vehicles are suggested on the bottom line. If we can avoid extensive requalification of the spacecraft between each use and avoid a large sustaining cost for the launch vehicle it seems reasonable to assume that we can attain the cost levels shown. In terms of $/man in orbit this means we can launch a man together with enough supplies for three months at approximately $3M. This compares with a cost of about $30M/man using the Saturn IB - Apollo system. Large experiment modules can be launched at a cost of about $250/lb which is probably a small fraction of their development and production costs.

In order to further reduce the costs to levels below those just discussed, it is necessary to consider ways of recovering and reusing more of the launch vehicle propulsion. Since we must in any event recover the spacecraft, it seems logical to look at configurations in which this propulsion is carried by the spacecraft. When we do this, the spacecraft tends to become too long and narrow for vertical landing and more compatible with the horizontal landing concepts.

While this approach has seen a substantial amount of research, including flight research with the M2/F2 and the HL[10] lifting body configurations, it is a departure from our past operational experience and these are termed Class II vehicles. This class of vehicle comprises a reusable core spacecraft having integrated upper stage propulsion, expendable fuel tanks, and in general an expendable 1st stage, as indicated in the middle configuration of Figure 5.

The question of whether an expendable 1st stage or expendable tip tanks on the upper stage is to be preferred depends on both performance and cost considerations, and it is interesting to compare these two approaches.

CLASS II SYSTEMS

In Figure 6 is shown the upper stage spacecraft weight plotted against the lower stage weight. The general trend, as you might expect, is that of increasing the upper stage weight in order to provide an adequate velocity increment as the lower stage weight, and therefore its velocity increment, is reduced. On the extreme right, the upper stage weight is that of the recoverable core and its propellant and the lower stage comprises three solid rockets; as we move to the left, upper stage expendable tanks are added and the lower stage reduced to one solid rocket. Finally, at the extreme left the tanks become very large and the first stage is dispensed with entirely.

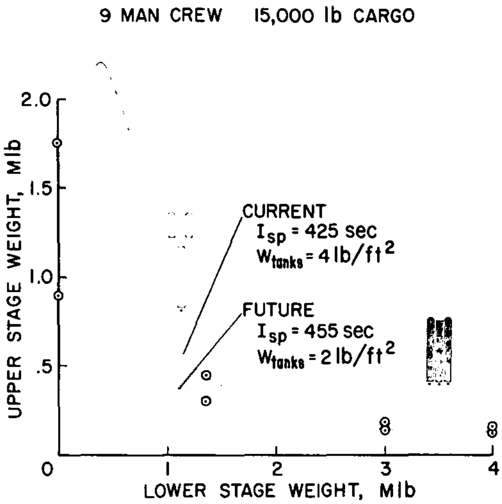


FIGURE 6 - Class II Systems — Performance

Two curves are shown, the upper curve corresponding to current propulsion technology; I_{SP}=425 and tank weights of approximately 4 lb/sq.ft typical of S-IVB and S-II Stage Cryogenic tanks. The lower curve corresponds to a situation wherein the I_{SP} has been increased to 455 secs and tank weights reduced to 2 lb/sq.ft. Needless to say, this low value of tank weight per unit area represents a rather large step beyond the current state-of-the-art for insulated cryogenic tanks, particularly in the configuration on the left where the tanks sustain aerodynamic as well as inertial loads, and are subject to aerodynamic heating during exit from the atmosphere. From the extent of the shaded region it is also clear that when the lower stage weight is reduced below about 1 million pounds, the upper stage weight becomes very sensitive to the assumed improvements in I_{SP} and tank weight.

If we accept that the improvements in performance represented by the lower curve are attainable, it is interesting to look at the changes in cost per flight as we traverse this same spectrum of configurations. On the left hand side of Figure 7 is shown the cost/flight in $M plotted against lower stage weight. In general, there are three contributing cost elements corresponding to refurbishment of the upper stage core, cost of the upper stage expendable tanks and cost of the lower stage.

At the extreme left, the configuration has no expendable lower stage and the cost is the sum of the core refurbishment cost and throw-away tank costs. Moving to the right, the expendable lower stage costs begin to appear but the tanks become smaller and the costs decrease, until finally no tip tanks are required at about 3 million pounds lower stage weight.

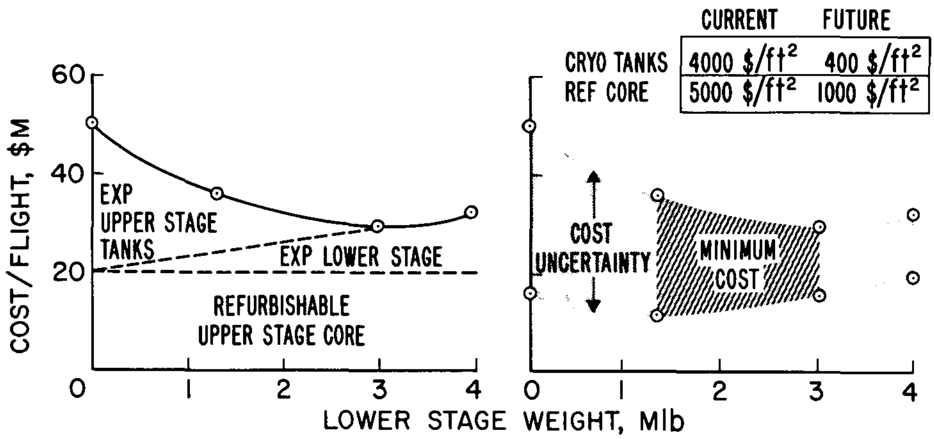


FIGURE 7 - Class II Systems — Cost/Flight

The total cost curve has been transferred over to the right as the upper curve and there appears to be a cost minimum of about $30M/flight when the lower stage weight is about 3 million pounds. Evidently, the current situation is that expendable lower stages are less costly than expendable tanks. Current costs are approximately $4,000/sq. ft. for cryogenic tanks and estimated at $5,000/sq. ft. for the core vehicle refurbishment. The tank costs are based on Centaur, S-IVB and S-II costs; the core refurbishment costs are based on estimates of what refurbishment and requalification would cost using current test philosophy.

In recent months, there has been some study of the design of cryogenic tanks which in addition to being half the weight, would also be substantially less costly than current tanks. Such tanks are envisioned as being of "non-space" design, using aluminum primarily, but with stainless steel nosecaps, and would not require the expensive chemical milling of current practice. Furthermore, it is assumed that these tanks would not undergo the extensive test program required for present day tanks.

While such a development may be many years away, it is interesting to speculate on what the effect would be on the cost/flight of the logistics system. The situation is represented by the lower curve where now the cryogenic tanks costs have been reduced by a factor of 10, and the core refurbishment costs by a factor of 5. The result, of course, is a substantial reduction but even here the minimum cost configuration uses an approximately 1 million pounds lower stage. For costs that vary between the extremes given here, it appears that the preferred configurations have a first stage weighing between 1 and 3 million pounds.

The extent to which the Class II can approach these lower cost levels depends very much on whether we can simultaneously reduce both the weight and the cost of cryogenic tanks, and to the extent to which we can relax the stringent test procedures for those tanks and for refurbishment of the core vehicle. In the event these steps are taken, the primary source of cost would reside with the expendable lower stage. Still further reductions in cost would then depend on whether a reusable lower stage could be developed, leading to the Class III vehicles--fully reusable, either an airbreathing Horizontal Takeoff-Horizontal Landing system or Rocket Vertical Takeoff-Horizontal Landing system.

CLASS III SYSTEMS

These Class III vehicles are depicted in Figure 8 where, as before, upper stage weight is plotted vertically and lower stage weight horizontally. Looking first at the airbreathing system depicted on the left, the same trend is present: upper stage weight increases as lower stage weight decreases; the shaded band shows the weight reductions that result from the use of a Scramjet as compared with the subsonic Ramjet. There are certain limitations on the weight of the first stage however. If it is made too large compared with the upper stage, it attempts to supply too great a velocity increment and runs out of atmosphere, and exceeds Mach numbers which are feasible. On the other hand, if the lower stage is too small, the upper stage weight must increase in order to provide the required ΔV, and the two stages become incompatible with respect to size, as indicated by the left hand boundary.

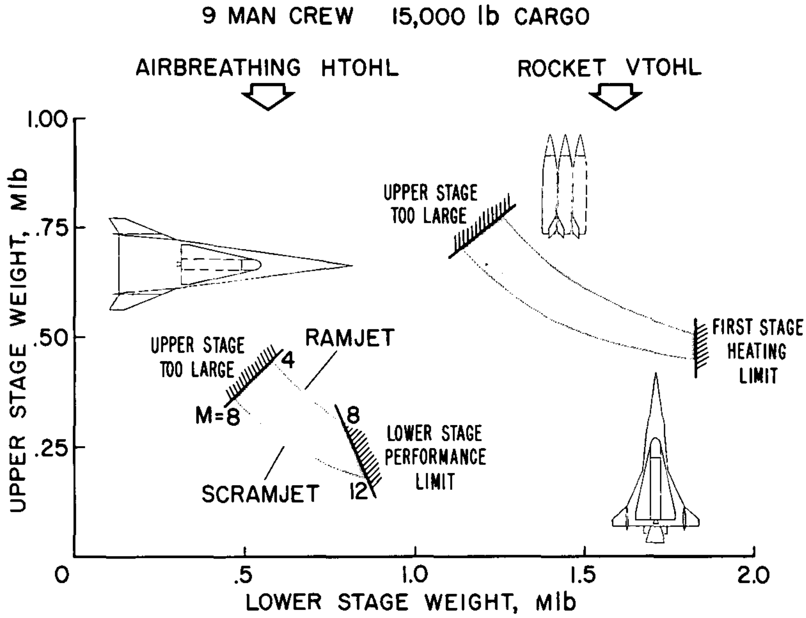


FIGURE 8 - Class III Systems — Performance

A somewhat similar situation holds also for the Vertical Takeoff Rocket depicted at the lower right. As the lower stage becomes larger it provides more velocity and necessarily faces greater heating problems in its suborbital entry into the atmosphere prior to flying back to the launch site. The right hand limit shown here corresponds to the velocity at which its radiatively cooled structure exceeds design temperatures. Going beyond the limit would require an ablatively cooled lower stage with attendant large increases in stage weight. The left hand limit for the Vertical Takeoff Rocket results from a configuration size incompatibility between lower and upper stage. In this situation, configuration like the triamese concept may be preferred as shown in the upper right. The lower stage now comprises two outer flyback rockets whereas the middle (2nd stage) rocket goes on to orbit. Here the lower stage weighs approximately twice the upper stage.

The feasibility of all of the Class III systems depends very much on how much technical progress is made during the next ten years. For the reusable lower stage to be attractive it must have efficient aerodynamics, structures and propulsion; moreover, because of the large volume that must be provided for the hydrogen fuel and because of the large engine in the case of the airbreathing systems, there are major interactions between aerodynamic and structural design and between aerodynamics and propulsive performance.

In order to be complete, some discussion of the cost per flight for these fully reusable systems is in order. The whole philosophy behind this approach to orbital transportation is that the vehicle should operate like an airplane in the sense that each flight would require only routine checkout and refueling, and would entail a relatively small ground crew. The system would employ ample redundancy in its critical subsystems, so that all failures would be benign, and either correctable by the flight crew or of such a nature that the mission could be aborted safely.

This is the right way to think about orbital transportation; at the same time, though, there are major differences in the environment to which the system is subjected, as compared with that of high speed airplanes, even the X-15 and B-70, and routine turnaround and reflight, which is basic to low cost, may be some distance into the future. Consequently, any estimate of operational costs for these Class III systems have a great deal of uncertainty, and cannot be validated until acceptable reflight test and certification procedures are decided upon. These in turn depend on our level of confidence and understanding of the environmental effects on the system. It is necessary to pursue a vigorous technology program before we can proceed to the development of Class III systems.

CLASS I, II, III SYSTEM DEVELOPMENT COSTS

Let me summarize the cost picture, such as we understand it, for the three classes. So far, only the cost per flight has been discussed whereas the development cost is also important since it determines in part whether the system is economically feasible. In Figure 9, the cost per flight is plotted on a logarithmic scale against the estimated development cost, on the horizontal scale. The Class I systems fall in the range \$100M to \$20M, the lower value corresponding to a reusable crew module, a reusable propulsion module, and a low cost solid rocket launch vehicle. Based on past development costs of Gemini, Apollo CM and Apollo SM, development costs of the order of \$2B are estimated. It seems reasonable to expect that we could develop this system by 1975.

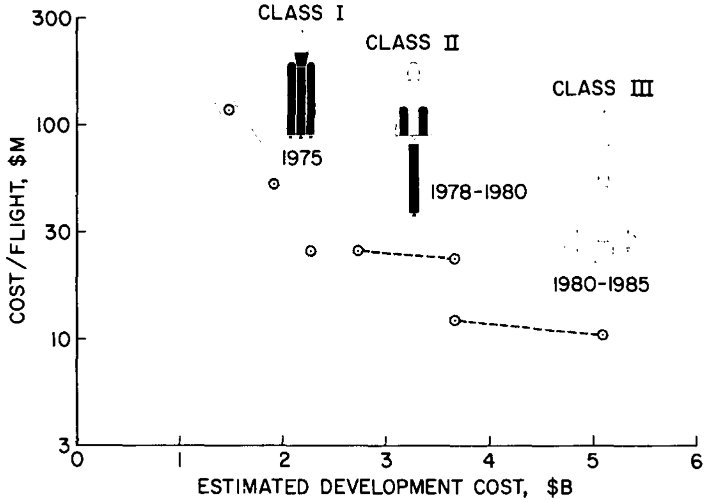


FIGURE 9 - Cost Summary

Costs for the Class II systems depend on refurbishment costs for the upper stage core vehicle and in the costs of expendable tanks. The shaded region reflects this cost uncertainty which is greatest for those configurations using large tanks--the stage and a half system particularly. Because of the departure of these concepts from past designs, they are likely to have greater development costs, of the order of \$3B or more, and will take longer to bring to operational status.

The Class III systems are much more difficult to assess in regard to their development costs and the shaded region shown here covers a range of estimates made by various past studies. As a point of comparison, the development cost of the B-70 was about \$1.5B, and for the SST is probably in the neighborhood of \$2.5-\$3.0B. The estimated development times are correspondingly larger too and 1980-1985 is probably an optimistic timescale if we are to proceed in a technically responsible way.

REQUIRED TECHNOLOGY

I have attempted to summarize the various pieces of technology required in the future in Figure 10. On the left are the three classes and the systems they use. Along the top are the associated areas of technology that need to be advanced in order to develop these systems, grouped into two categories--space vehicles and propulsion. The Class I systems require little in the way of fundamentally new technology and the items listed are really development items. In Class II, the reusable lifting core vehicle with an integrated propulsion system would require further wind tunnel and flight testing, the question of horizontal landing without go-around capability should be resolved, and the combined aerodynamic and structural performance of this concept should be assessed more accurately.

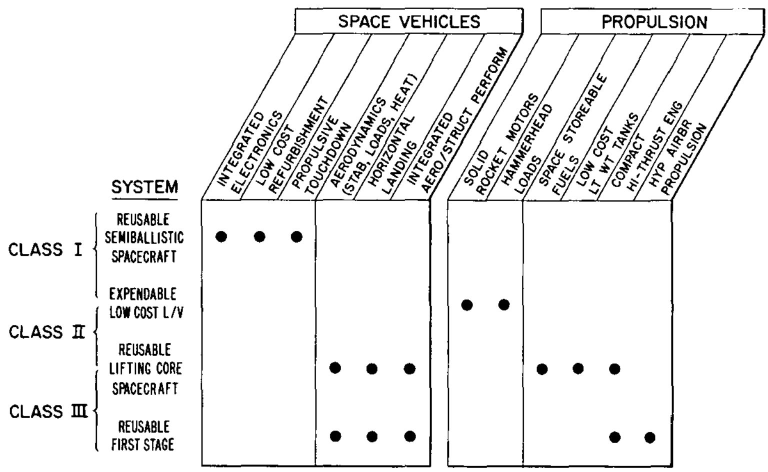


FIGURE 10 - Technology Summary

On the propulsion side, space storable fuels look to be attractive, particularly if the cost of hydrogen tanks remains high. The design of low cost, light weight, cryogenic tanks is a major technical challenge. As we attempt to integrate propulsion into the spacecraft, the need for compact, high-thrust engines is apparent, and the current work within the Industry should be very valuable in this context.

The reusable first stage has somewhat similar problems in the core spacecraft, although in a large size configuration: aerodynamics, landing, structural performance. Again compact, high-thrust, engines are important; and, for the horizontal takeoff system, hypersonic airbreathing propulsion and its integration with the structure and aerodynamics are items of technology that require a sustained effort of several years duration.

CONCLUSIONS

Reductions in the cost of transportation to orbit of the order of a factor of 10 appear feasible with essentially current technology, if the transportation system evolves from present systems and if the low cost operating mode is accepted. Further reductions, based on concepts that differ from past systems, depend on the development of combined launch vehicle/spacecraft configurations in which a major part of the propulsion is recovered and reused; the extent of these cost reductions depends on both technical advances and the acceptance of a new operational philosophy.